On the NuTeV anomaly and the asymmetry of the strange sea in the nucleon

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Abstract

Our recent theoretical analysis based on the flavor SU(3) chiral quark soliton model predicts fairly large particle-antiparticle asymmetry of the strange sea in the nucleon. We point out that the predicted magnitude of asymmetry is large enough to solely resolve the so-called NuTeV anomaly on the fundamental parameter $\sin^2\theta_W$ in the standard model.

At the early stage of high-energy deep-inelastic scattering analyses, it was a common assumption that the sea quark distributions in the nucleon are flavor SU(3) symmetric. It is clear by now, however, that there is no sound theoretical reason to justify this dogma. In fact, the isospin SU(2) asymmetry of the nucleon sea, i.e. the asymmetry of $\bar{u}$ and $\bar{d}$ distributions in the proton has been definitely established by the NMC measurement [1]–[4]. Similarly, it is highly probable that the momentum distributions of strange quarks and antiquarks are not the same despite the constraint that the total numbers of s- and $\bar{s}$-quarks are precisely equal in the nucleon [5] -[10]. The possible asymmetry of the s- and $\bar{s}$-quark distributions in the nucleon has attracted a renewed interest after it was recognized that it plays a crucial rule in the interpretation of NuTeV determination of the weak mixing angle [11] –[17]. The NuTeV Collaboration extracted the value of $\sin^2\theta_W$ by measuring the ratio of neutrino neutral-current and charged-current cross sections on iron. The measured ratio R^- (the so-called Paschos-Wolfenstein ratio [18]) is related to the Weinberg angle θ_W by [13] –[16]

$$
\begin{aligned}
R^- &\equiv \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} \\
&= \frac{1}{2} - \sin^2\theta_W + \delta R_A^- + \delta R_{QCD}^- + \delta R_{EW}^-,
\end{aligned} \tag{1}
$$

where the three correction terms respectively stand for the target non-isoscalarity correction (δR_A^-), QCD corrections (δR_{QCD}^-) and higher-order electroweak corrections (δR_{EW}^-). The QCD corrections come from three main sources as

$$\delta R_{QCD}^- = \delta R_s^- + \delta R_I^- + \delta R_{NLO}^-, \tag{2}$$

where $\delta R_s^-, \delta R_I^-$ and δR_{NLO}^- respectively stand for possible strange-sea asymmetry ($s^- \equiv s - \bar{s} \neq 0$), isospin violation ($u_{p,n} \neq d_{n,p}$) effects in the parton density of the nucleon, and the NLO corrections. In the present study, we focus on the first correction due to the possible asymmetry of the strange sea in the nucleon. Approximately, it is given by [13]

$$\delta R_s^- \simeq -\left(\frac{1}{2} - \frac{7}{6}\sin^2\theta_W\right)\frac{[S^-]}{[Q^-]}, \tag{3}$$

where

$$[S^-] \equiv \int_0^1 x\,[s(x) - \bar{s}(x)]dx, \tag{4}$$

$$[Q^-] \equiv \int_0^1 x\,[u(x) - \bar{u}(x) + d(x) - \bar{d}(x)]dx. \tag{5}$$

Recently, the CTEQ group performed a global PDF fit including the NuTeV "dimuon events" on the neutrino and antineutrino-production of charm [14, 15]. Their analysis leads to a central value $[S^-] \simeq 0.002$ and conservative bound

$$-0.001 < [S^-] < 0.004. \tag{6}$$

Note that the positive moment $[S^-]$, which means that the momentum distributions of the s-quark is harder than that of the $\bar{s}$-quark in the nucleon, works to reduce the discrepancy between the NuTeV determination of $\sin^2\theta_W$ [11, 12] and the world average of other measurements [19].

Since the distribution of sea quarks and antiquarks generated through the perturbative QCD evolution are necessarily CP symmetric, the cause of asymmetry of the nucleon strange sea must be of nonperturbative origin. (Note however the recent claim that the three loop QCD correction may generate a sizable strange-quark asymmetry in the nucleon [20].) As discussed by many authors, the most plausible source of the asymmetry may be the virtual fluctuation process of the physical proton into the ΛK^+ intermediate state [5] –[10]. Since the s- and $\bar{s}$-quarks in the intermediate state are contained in totally different type of hadrons, i.e. a baryon and a meson, their helicity and momentum distribution can be significantly different. It was argued that this "kaon-cloud picture" of the nucleon leads to several interesting predictions, such as

(1) s-quarks carry more momentum fraction, than $\bar{s}$-quarks, i.e. $\int_0^1 xs(x)dx > \int_0^1 x\bar{s}(x)dx$.

(2) s-quarks are polarized antiparallel to the initial proton spin.

Although intuitively very appealing (and we believe it contains a piece of the truth), the predictions of the kaon-cloud model should be taken as only suggestive. The reason is clear. For obtaining the desired strange and antistrange distributions of the nucleon in this model, one need two basic quantities which are not known very well. The one is the so-called meson-cloud-model *fluctuation functions*, which give the probability to find the baryon or meson with some longitudinal momentum fraction. The other is the strange valence parton distributions of the *constituents of cloud*, i.e. Λ and K^+. Even worse, it is far from clear how many mesons, besides the pseudoscalar octet, one should take into account. In fact, in a recent paper, Cao and Signal estimated the strange sea distributions

by taking account not only of $p \to \Lambda K^+$ fluctuation, but also of some other fluctuations into $\Lambda K^{*-}, \Sigma K$ and ΣK intermediate states [8]. Embarrassingly, their conclusion was that the s-$\bar{s}$ momentum asymmetry generated by the ΛK^+ fluctuation is cancelled nearly completely by the fluctuation containing K^* clouds.

Obviously, what we need is more systematic approach, which is free from the above-mentioned theoretical ambiguities. We claim that chiral quark soliton model (CQSM) is the best candidate to meet such requirements. The great advantage of this effective quark model is that the Goldstone bosons appear (automatically) as composites [21, 22], which enables us to introduce effects of meson cloud without worrying about many ambiguities and complexities inherent in the meson-cloud convolution model. It has already been shown that, without introducing any adjustable parameter except for the initial-energy scale of the Q^2-evolution, the CQSM can explain nearly all the qualitatively noticeable features of the recent high-energy deep-inelastic scattering observables [23] -[31]. It naturally explains the excess of $\bar{d}$-sea over the $\bar{u}$-sea in the proton [4, 27, 28]. It also reproduces the characteristic features of the observed longitudinally polarized structure functions for the proton, the neutron and the deuteron [29]. The most puzzling observation, i.e. unexpectedly small quark spin fraction of the nucleon, can also be explained in no need of large gluon polarization at the low renormalization scale [22, 30, 31]. Recently, we have also addressed the problem of quark-antiquark asymmetry of the nucleon strange sea distribution based on the CQSM generalized to flavor SU(3) [32, 33]. (See also [34].) It turned out that the predictions of the SU(3) CQSM supports the general idea of the most naive kaon cloud model at least qualitatively. It predicts a sizable amount of s-$\bar{s}$ momentum asymmetry in such a way that $\int_0^1 xs(x)dx > \int_0^1 x\bar{s}(x)dx$. It also predicts that the s-quark is negatively polarized with respect to the proton spin direction, while the polarization of $\bar{s}$-quark is relatively small. In consideration of the impact of the NuTeV anomaly, here we reexamine the problem of the s-$\bar{s}$ momentum asymmetry and see what this unique model can say about it.

The basic Lagrangian of the SU(3) CQSM is given as

$$\mathcal{L} = \bar{\psi}(x)(i \not\partial - MU^{\gamma_5}(x) - \Delta m_s P_s)\psi(x), \tag{7}$$

with

$$U^{\gamma_5}(x) = e^{i\gamma_5 \pi(x)/f_\pi}, \quad \pi(x) = \sum_{a=1}^{8} \pi_a(x)\lambda_a, \tag{8}$$

and

$$\Delta m_s P_s = \Delta m_s \left(\frac{1}{3} - \frac{1}{\sqrt{3}} \lambda_8 \right) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Delta m_s \end{pmatrix}. \tag{9}$$

It is a straightforward generalization of the corresponding SU(2) model, except for one important new feature, i.e. the presence of the sizably large SU(3) symmetry breaking term arising from the effective mass difference Δm_s between the strange and nonstrange quarks. Since the dynamical quark mass M is already fixed to the value $M \simeq 375\,\mathrm{MeV}$ from the phenomenology of nucleon low energy observables within the SU(2) model, this mass difference Δm_s is the *only one additional parameter* in the flavor SU(3) generalization of the CQSM. Since the detail of the model was already explained in [32, 33], here we only want to emphasize that the SU(3) symmetry breaking effects can be estimated by using the first order perturbation theory in the parameter Δm_s. We believe this treatment is justified (at least partially), since the effective mass difference Δm_s of the order of 100 MeV is much smaller than the typical energy scale of baryons. Naturally, the most sensitive quantities to the parameter Δm_s are magnitudes of the s- and $\bar{s}$-quark distributions. In [32], we determined Δm_s so as to reproduce the CCFR data for $s(x)$ and $\bar{s}(x)$ distribution, which was extracted under the constraint $s(x) = \bar{s}(x)$. The overall success of the theory is obtained with the value of Δm_s around 100 MeV.

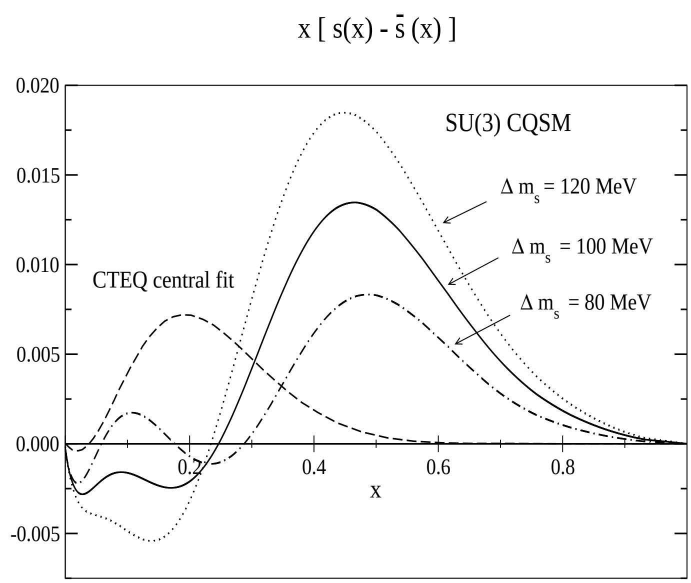

FIG. 1: The theoretical predictions of the SU(3) CQSM for $x[s(x) - \bar{s}(x)]$ evolved to $Q^2 = 16\,\mathrm{GeV}^2$ with $\Delta m_s = 80\,\mathrm{MeV}$, $100\,\mathrm{MeV}$ and $120\,\mathrm{MeV}$ in comparison with the CTEQ central fit.

As discussed in [32], the difference function $s(x) - \bar{s}(x)$ is also very sensitive to the SU(3) symmetry breaking effect. Here we examine the effect of the variation of the parameter Δm_s around its central value above to see its influence on the NuTeV analysis. Shown in Fig.1 are the theoretical predictions of the SU(3) CQSM for $x[s(x) - \bar{s}(x)]$. Here the dash-dotted, the solid and the dotted curves are obtained with $\Delta m_s = 80\,\mathrm{MeV}$, 100 MeV and 120 MeV, respectively. Also shown for comparison is the central fit of the CTEQ group (dashed curve). In view of the sizably large uncertainties coming from using the neutrino data on nuclear target, the qualitative agreement between the theory and CTEQ fit seems encouraging. One clearly sees a common tendency in the results of the two analyses, which are of totally different nature. Both shows that the momentum distributions of the s-quark is harder than that of the $\bar{s}$-quark. Now the question is the size or the magnitude of the predicted momentum asymmetry.

TABLE I: The prediction of the SU(3) CQSM for the second moments $[S^-]$, $[Q^-]$ and the correction δR_s^- to the Paschos-Wolfenstwein ratio R^- in dependence of Δm_s.

Δm_s (MeV)	80	100	120
S^-	0.0025	0.0040	0.0055
Q^-	0.226	0.227	0.228
δR_s^-	- 0.0034	- 0.0055	- 0.0075

The crucial quantities here are the second moments $[S^-]$ and $[Q^-]$ defined in (4),(5), which in turn give δR_s^- according to (3). We show in table 1 the predictions of the SU(3) CQSM for $[S^-]$, $[Q^-]$ and δR_s^- obtained with the three choices of the parameter Δm_s, i.e. $\Delta m_s = 80\,\mathrm{MeV}$, $100\,\mathrm{MeV}$, and $120\,\mathrm{MeV}$. The CQSM prediction for $[S^-]$ ranges from 0.0025 to 0.0055 with the central value

$$[S^-]_{CQSM} = +0.004, \tag{10}$$

corresponding to the above choices of Δm_s. This prediction may be compared with the central value

$$[S^-]_{CTEQ} = +0.002, \tag{11}$$

and the conservative bounds

$$- 0.001 < [S^-]_{CTEQ} < +0.004, \qquad (12)$$

obtained by the CTEQ PDF fit. Translating into a shift of the Weinberg angle, the SU(3) CQSM gives

$$- 0.0075 < \delta(\sin^2 \theta_W)_{CQSM} < -0.0034, \qquad (13)$$

with the central value $\delta(\sin^2 \theta_W)_{CQSM} = -0.0055$. Note that the central value obtained with $\Delta m_s = 100\,\mathrm{MeV}$ is large enough to fill a gap between the NuTeV determination of $\sin^2 \theta_W$ $(0.2277 \pm 0.0013 \pm 0.0009)$ and the world average of other measurements (0.2227 ± 0.0004). Even the conservative estimate obtained with a smaller value of $\Delta m_s = 80\,\mathrm{MeV}$ explains nearly 70 % of the discrepancy.

To summarize, before extracting any new physics beyond the standard model from the NuTeV anomaly, one should first worry about theoretical uncertainties mainly due to QCD. Undoubtedly, the possible asymmetry of the strange sea in the nucleon is one of the most important factors that we must take seriously. In fact, the existence of the asymmetry seems an unavoidable physical consequence of chiral symmetry of QCD. The widely-accepted scenario of spontaneous breakdown of this symmetry dictates the appearance of low mass pseudoscalar octet, which in turn make these mesons the source of the energetically lowest excitation of nucleon with intrinsically generated sea quarks. This scenario, which is completely consistent with the well-established dominance of the $\bar{d}$-sea over the $\bar{u}$-sea in the proton, also indicates the asymmetry of nucleon strange sea. Unfortunately, the simplest candidate, i.e. the meson-cloud convolution model, which realizes this idea in the most direct way, suffers from several theoretical uncertainties and its predictions are now widely diverse. This is to be contrasted with the flavor SU(3) generalization of the CQSM. Only one parameter of this model is the effective mass difference between the strange and nonstrange quarks, which gives the measure of the SU(3) symmetry breaking. Within the reasonable range of this parameter, the SU(3) CQSM has been shown to predict a sizable amount of asymmetry of the s- and $\bar{s}$-quark distributions in the nucleon, which is large enough to resolve the NuTeV anomaly. In any case, one important fact has become apparent through the investigations inspired by the NuTeV report. The neutrino-induced DIS measurement has become close to practical use as a tool to probe the internal structure of the nucleon. We expect that neutrino DIS scattering experiments to be carried out in the near future

will enable direct and more accurate determination of the light-flavor sea-quark distribution functions in the nucleon.

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